Human bond communications

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Human Bond Communications: Architectures, Challenges and Possibilities

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***Abstract*—Recent advancements in wireless networks and sensor technologies have enabled continuous monitoring of remote patients. This has opened doors for exploring new frontiers in the domain of smart health-care especially patient monitoring and diagnosis. Scientists and researchers have scouted the novel domain of human bond communications (HBC), which suggests detection and transmission of information using all five human senses (sight, smell, sound, touch, and taste). HBC not only enables these senses to be replicated at a remote location but also helps in diagnosis of several ailments through monitoring. Such a holistic communication medium is facilitated through specialized devices that help health-care experts in making crucial and timely data driven decisions for their patients. In this work, we present state of the art research on HBC and possible interactions between HBC and remote health-care. We present a model HBC framework to assist monitoring and diagnosis of Attention Deficit Hyperactivity Disorder (ADHD) patients. We also mention possible applications as well as challenges posed by HBC applications.**

***Index Terms*—human bond communication, remote health-care, sensory substitution, patient monitoring.**

I. Introduction

THE need for improved health-care services is two-fold in a society where aged, disabled and people with specialized ailments cover a large subset of population. In this era of smart health [1], wide adoption of ubiquitous computing and mobile communications has increased ease of use in personalized medicine. Future communication systems would make everyday interactions even more holistic [2]. Human bond communication aspires to achieve this goal by integration, digitization, transmission and replication of human five senses by considering human body as a Node (ByN) for future ICT[3].

Several technical challenges in detection and stimulation of chemical senses have been met with the help of electronic detection and stimulating systems. Three of the human five senses, touch, taste and smell, have complex representations, and because they are not simple wave forms, their digital transmission is faced with serious technical challenges [4].

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So far, digital detection and stimulation systems have been employed for commercial purposes, however, prospects of their usage in health-care applications has been supported by evidences in literature. HBC facilitates this prospect with the help of specialized devices called Senducers, Human Bond Sensorium (HBS) and Human Perceivable Transposer (HPT) [3].

In this work, we review technologies that enable implementation of HBC in health-care domain. We propose an architecture of HBC application for monitoring and diagnosis of Attention Deficit Hyperactivity Disorder (ADHD). We also discuss possible applications of HBC beyond health-care along with challenges which need to be addressed.

Rest of the paper is organized as follows: After giving readers some back ground knowledge in Section II, we present state of the art tools and technologies that have contributed to HBC literature in Section III. We also review studies that report diseases with sensory impairments, re-emphasizing the need to digitize the chemical senses. Section IV proposes a model framework required for monitoring and diagnosis of Attention Deficit Hyperactivity Disorder (ADHD) and along with that we present challenges which are faced in V. In Section VI, there is a brief discussion on possibilities of HBC applications beyond health-care. Finally, in section VII, we conclude our work highlighting the future directions and some of the key challenges to be addressed.

II. Background

Working mechanism of human bond communication architecture, visualized in Fig. 1, comprises of Senducers, Human

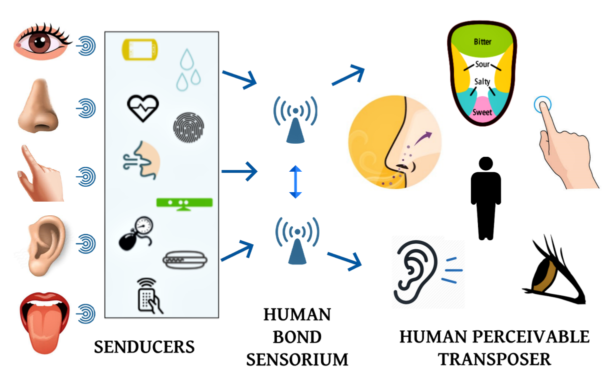

Fig. 1. Artifacts and components on a model Human Bond Communication Architecture.

Bond Sensorium (HBS) and Human Perceivable Transposer (HPT):

1) **Sense Transducer or Senducer**: In a health-care setting, a patient's tactile information is gathered by tactile sense transducers. Information of smell and taste perception is gathered by olfactory and gustatory sense transducers, respectively. This sensory information is sent to Human Bond Sensorium (HBS) which acts as a gateway node for all senducers. Where interpretation of a physical subject in five human sensing domains is performed followed by transformation of this information into electrical signals and transmission of sampled information to HBS is done [3].
2) **Human Bond Sensorium (HBS)**: Acting as a gateway node, HBS receives data from senducers. While implementing procedures to ensure integrity, reliability and security, HBS processes and transmits incoming signals to Human Perceivable Transposer (HPT) at the receiver end.
3) **Human Perceivable Transposer (HPT)**: Once received, these signals are reconstructed into human perceivable formats. Reconstruction at the receiving end can be achieved via direct or indirect realization as depicted in Fig. 2.

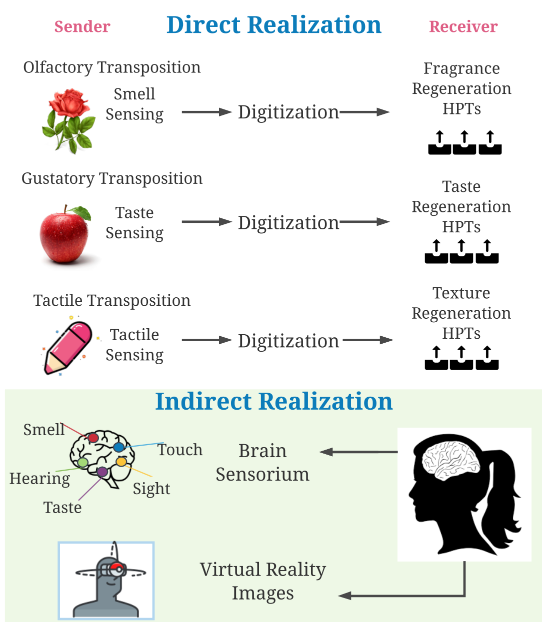

Fig. 2. Direct and Indirect Realization in HPT. After detection and digitization of three senses, smell, taste and tactile, these properties are reconstructed by HPT devices at the receiver end. Indirect realization can be achieved either by interacting with brain sensorium that incites feelings, or by creating virtual reality images displaying properties of an object.

In direct realization, olfactory, gustatory and tactile performance is tested by taking inputs from the patient. Cartridges inside test devices carry samples of fragrance or odor, taste of edible items and texture of different objects. The patient identifies taste, smell or touch of these objects on a given scale through the interface provided by these testing devices. After having digitized patient's performance, this data is transmitted over a network to HPT devices at the physician's end. HPT devices will reconstruct taste/smell/touch of objects. Patient performance is analyzed and compared with respective reference values. A report of differences between reference and user perceived values are displayed to the physician for decision system.

On the other hand, indirect realization of chemical senses can also be achieved. In this method, optical and aural data of an object is used to create high definition (HD) virtual reality images of the object. This visualization is representative of taste/smell/tactile properties of that object. Simulations can be created for identifying the sensory information of patient's brain actuated by electrical stimulation in response to the olfactory, gustatory and tactile stimuli, or for watching a virtual display of the location/area of pain on patient body. Another way of indirect realization is via Brain Sensorium, where all sensory stimuli are received, processed and interpreted by the brain. Sensory perceptions are generated at the receiver end by registering electronic / digital stimuli.

The holistic communication system of HBC can be materialized effectively and efficiently by utilizing sensing and transmission technologies with the following properties:

- **Sensing**: HBC sensors need to exhibit the ability to sense a large range of physical traits and the capability of discriminating between strengths of a physical property [3]. They should be automatic, location-aware, flexible, low cost and non-invasive in nature. Technologies like Ultra-Wide Band (UWB) can be used for accurate on and in-body localization of sensors [5]. One design decision is whether one or more sensor nodes need to be deployed for sensory data collection. An appropriate sensor fusion strategy is used to avoid limitations of spatial coverage, sensor deprivation, imprecision and uncertainty [6].
- **Networking**: Remote monitoring of physiological signs are enabled by leveraging Wireless Body Area Network (WBAN) technologies. Key performance gains of using 5G for HBC have been summarized in [5]. Efficient transmission of multi-sensory data can also be done using various transmission mechanisms. Bluetooth, WiFi, LoraWAN and 5G all help build an ubiquitous ultra broadband network specially designed while keeping in mind low power consumption and efficient transmission [7].

III. Literature Review

The human tongue can identify and distinguish a few basic tastes yet the human nose can identify a trillion smells. It is much easier to reach the taste buds on tongue than trying to reach the complex structure of olfactory receptors inside nose. Digitization of olfactory, gustatory and tactile senses is limited to ambient scent delivery, taste differentiation systems and stimulating vibrations for immersive experiences. So far, in commercial applications, perceivable transposers have been used to reproduce scents, tastes and textures using knowledge from chemical and material sciences domains.

Currently, it is not possible to transmit the whole array of olfactory, gustatory and tactile receptors. Kenneth Suslick [8],

TABLE I
STATE OF THE ART IN SENSORS (S_X) AND DEVICES (D_X) FOR OLFACTORY (O), GUSTATORY (G) AND TACTILE (T). NOTE: WEARABLE (W), IMPLANTABLE (I) OR MOUNTED IN SURROUNDING (S).

Sr. No.	Authors/Inventors, Year	Name	Function	W	I	S	O	G	T
D_1	M. J. Lee and H. C. Lee, 2016	US9351658B2	Device and method for sensing electrical activity in tissue	✓	×	×	×	×	✓
D_2	D. Edwards, 2014	oPhone Duo	Scent-Based Mobile Messaging	×	×	✓	✓	×	×
S_1	Y. Fu et al.,2017	Self-powered, stretchable, fiber-based electronic-skin	for actively detecting human motion and environmental atmosphere	×	✓	✓	×	✓	×
S_2	K. Woertz et al, 2011	Astree II and TS-5000Z	two electronic tongues for pharmaceutical formulation development	×	×	✓	×	✓	×
D_3	S.W. Kim et al., 2017	A Triple-Mode Flexible E-Skin Sensor Interface	for wireless sensing pulse wave, voice, chewing / swallowing, breathing, knee movements and temperature	✓	×	×	×	×	✓
S_3	N.Ranasinghe et al., 2017	Lemonade Simulator	Digitally shares the color and flavor experience of a glass of lemonade	×	×	✓	×	✓	✓
D_4	A.D.Cheok, 2018	Electrical tongue stimulation device	Electric Taste	×	✓	×	×	✓	×
S_4	A. Agarwal, 2018	Axon VR, Synesthesia suit, Rapture Vest, Teslasuit	Putting AR/VR to work	✓	×	×	×	×	✓
D_5	A.D.Cheok, 2018	Digital Smell Interface	Digital interface for actuating smell sensations	✓	×	×	×	×	✓
D_6	A.D.Cheok et al, 2018	Electronic Taste and Thermal Machine	Digital taste actuation technology. Produces and modifies thermal taste sensations on the tongue	✓	×	✓	×	×	✓
D_7	J.R. Kozloski et al., 2018	US20180218268A1	System, method and computer program product for sensory stimulation to ameliorate a cognitive state	✓	×	×	×	×	✓
S_5	J.H.Tae and D. Yang, 2018	five sense experience kiosk	delivers five senses to a user	×	×	✓	✓	✓	✓
D_8	R.D. O'et al., 2012	WO2012112561A1	Wearable Personal Communicator Apparatus, System and Method for five senses	✓	×	×	✓	✓	✓
D_9	Y.L. Chan et al., 2017	US20170090446A1	Wearable Taste Generation Device	✓	×	×	×	✓	×
D_{10}	M. Johns and C. Hocking, 2011	US 2011/0121976A1	Alertness Sensing Device	✓	×	×	×	×	✓
S_6	S. Metzger, 2018	US20180221620A1	Modulation of brainwave activity using non-invasive stimulation of sensory pathways	✓	✓	✓	✓	×	×
D_{11}	R.B.Levin, 2000	US6167298A	Devices and methods for maintaining an alert state of consciousness through brain wave monitoring	✓	×	×	×	×	✓
S_7	N.O. Mahony et al., 2014	Inertial Measurement Units (IMUs)	Used to measure Physical Activity	✓	×	×	×	✓	×
S_8	M. Efrati, 2016	Tactile low frequency transducer	Vibrates over a range of frequencies in response to reception of a signal	✓	×	×	×	×	✓
D_{12}	D. J. Dilorenzo, 2016	US9375573B2	Systems and methods for monitoring a patient's neurological disease state	✓	×	✓	×	×	✓
D_{13}	E. Westenbrink et al., 2015	Electronic Nose	Development and application of a new electronic nose instrument for the detection of colorectal cancer	×	×	✓	✓	×	×
D_{14}	L.M.Zhou et al., 2018	US20180110981A1	System and method for perceiving smell remotely	✓	×	×	✓	×	×
S_9	Z.Zhang, 2012	Microsoft Kinect Sensor	Skeletal mapping	×	×	✓	×	×	✓
S_{10}	An Luo et al., 2012	US20120197092A1	Dry sensor EEG/EMG and Motion Sensing System	✓	×	×	×	×	✓
D_{15}	R.Swarts et al., 2018	PANDA: Paediatric attention-deficit/hyperactivity disorder app	differentiate between an ADHD and a non ADHD individual	×	×	✓	×	×	×
D_{16}	M.T. Choi et al., 2018	Robot-Assisted ADHD Screening in Diagnostic Process	classifies multiple categories of ADHD	×	×	✓	×	×	✓
D_{17}	Rizzo et al., 2000	Virtual Classroom	measure for the diagnosis and characterization of ADHD symptoms	×	×	✓	×	×	✓
D_{18}	D. Areces et al., 2016.	Aula Nesplora	Continuous Performance Tests (CPT) based virtual reality for ADHD diagnosis	×	×	✓	×	×	✓

a chemist and materials scientist at the University of Illinois at Urbana-Champaign, points out, "Anyone who's ever had a head cold knows that an awfully large fraction of what we call taste is actually smell." This interaction of taste with smell which is common in nature is another challenging feat to achieve in technological domain.

Table. I lists sensors, HPT devices, virtual reality environments and tools that are employed for materializing HBC applications especially for health-care. Sensory stimulation can provide non-pharmacological interventions to treat patients with altered sensory perceptions. It is evident that discontinuous exposure to odors improves general olfactory function in older people [9]. Multi-sensory stimulatory environments like Snoezelen have shown to positively impact on patients with emotional disorders in rehabilitative settings [10]. The virtual classroom developed by Rizzo depicts a good measure for the diagnosis and characterization of ADHD symptoms (see D_{17} in Table I.). Virtual Reality provides a more realistic and ecologically-valid assessment environment [11]. Ecological validity describes the degree to which a psychological test offers results similar to those found in real life [11].

In Singapore's Mixed Reality Lab, specialized environments have been developed where physical and digital objects are co-existing and interacting in real time, presenting the new Electronic Taste and Thermal Machine (D_6) in Table I by which a user's tongue, sandwiched between two metal sensors, would experience a virtual taste perception in brain. Taste discrimination systems like TS-5000Z quantify taste intensity using a taste scale. Similarly, Astree II e-tongue sensor can differentiate between solution samples. Both these electronic tongues (S_2) in Table I are compared and validated by K.Woertz et al for pharmaceutical formulation development.

D_2 mentions a device named oPhone Duo, which is capable of tagging 3000 aromas with a text message. This device can be used not only for tasting but also for sensory stimulation of patients with olfactory dysfunction. Not only that, it can also be used to evaluate olfactory performance of patients remotely. While it is possible to digitize and transpose taste and color of lemonade via the lemonade simulator (S_3), this experience is still incomplete without the smell of lemons. A method for perceiving smells remotely has been mentioned in (D_{14}) of Table I. Useful in the context of health-care, an electronic nose (D_{13}) in Table. I is developed for detection of colorectal cancer.

Tactile suits developed by AXON VR (now HaptX) for wholesome gaming experiences. Wearable 2.0 [12] is a health-care system for collecting users' physiological data, aided by cloud based intelligence.

Sensory dysfunction is among early markers for neuropsychiatric diseases, for example in depression and Attention Deficit Hyperactivity Disorder (ADHD). ADHD is characterized by attentional dysfunction, hyperactive / impulsive behaviours and affects both children and adults worldwide. Its etiology is not well known, therefore, there is a lack of agreement on an objective method of diagnosis for ADHD. It is hard to find concordance between adult-reported and clinician-rated symptoms specially in children. In this case parent-reported symptoms are mainly used for assessment [13]. ADHD patients have altered perceptual functions [13]. They exhibit atypical (both hypo- and hyper-) profiles of olfactory, gustatory, sensorimotor, somatosensorfunctionality and multisensory integration [14]. A positive relationship between abnormal sensory processing and ADHD traits has also been reported in general population [14]. In this paper, we leverage full potential of HBC in our proposed framework to assist in efficient monitoring and effective diagnosis of ADHD.

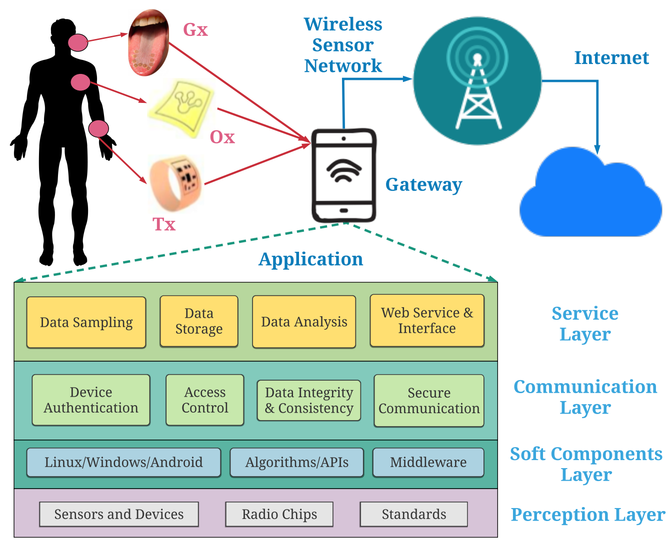

Fig. 3. Proposed architecture for HBC application comprising of gustatory (G_x), olfactory (O_x) and tactile (T_x) sensory to enhance detection and health-care service provision.

IV. HBC Application Architecture for ADHD Monitoring and Diagnosis

Judgments of clinicians are most widely accepted. Data collection, that assists these judgments (reviews and interviews), is a lengthy and difficult process to conduct. In this situation, objective measurements provide time and cost-effective ways to shorten overall assessment time, increase diagnostic accuracy, reduce delays in treatment and optimize the treatment response [15]. There is strong evidence base for the use of objective measures of activity to aid ADHD / non-ADHD group differentiation.

There are six commercially available Continuous Performance Tests (CPTs) currently in clinical use for diagnosis and monitoring of both medicated and medication naive ADHD patients. CPTs are task-based neuropsychological tests that measure sustained or selective attention and impulsivity in a sustained task [15]. Some CPTs measure two core symptoms of ADHD, activity level and impulsivity, via actigraphy devices, IMUs, or infrared devices. These devices capture movement but none of the approaches have incorporated gustatory and olfactory measurements in monitoring or diagnosis procedures.

We propose addition of gustatory and olfactory performance tests in ADHD monitoring and diagnosis. This can be achieved by employing a combination of enabling technologies such as (D_{15}) to (D_{18}) in Table I. In a similar way, (S_5) is a five sense experience kiosk that delivers touch, smell and taste

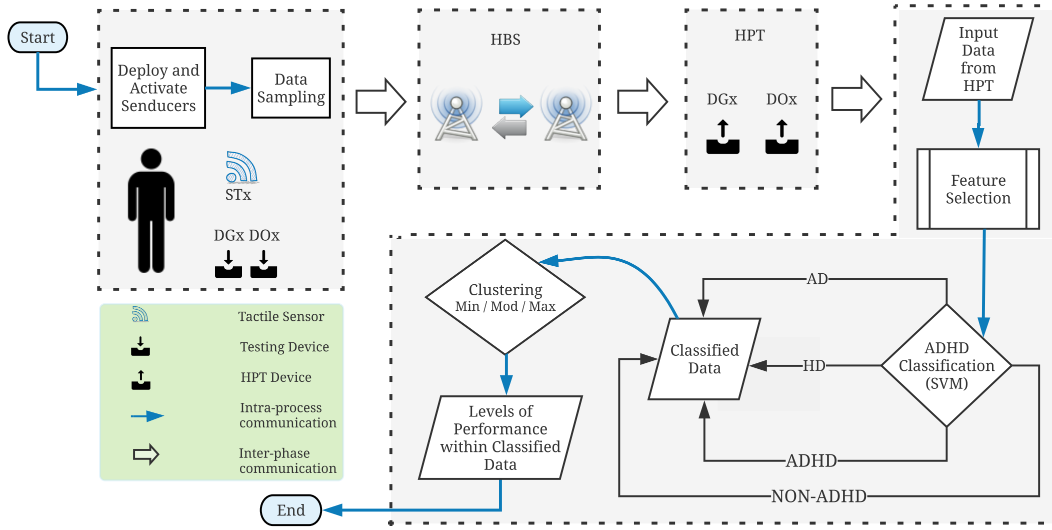

Fig. 4. Activity diagram of an HBC application for ADHD patients.

experiences to the user. (D_{14}) provides a method to convert brain waves (stimulated by an odorant) into a digital smell file, and converts a digital smell file into electric waves to simulate the olfactory bulb for restoring the smell associated with the digital smell file.

As evident from the above-mentioned literature, a typical gustatory and olfactory profiles in ADHD patients are added in diagnostic procedures of the ailment. In order to make ADHD monitoring and diagnosis multi-sensory, we propose combining CPT with gustatory and sensory information of patients. The proposed novel framework is used for collecting, transmitting and analyzing five-senses information of ADHD patient data for a holistic communication between patient and physician.

Fig. 3 shows an abstraction of proposed application architecture. The design constitutes four layers of interaction:

- **Service Layer** - Acting as interface layer, it gathers, analyses and assembles sensor data in a repository while presenting it for meaningful analytic processing and decision support systems.
- **Communication Layer** - This layer provides essential quality attributes to verify secure communication. Connection between application components are set up via standard APIs. Next, data is transmitted to the HBC receiver via a wireless network for fast and reliable communication.
- **Soft Components Layer** - Sense transducers leverage middle ware solutions, application logic, algorithms for data collection, sampling, processing, and transposers. Major processing tasks performed on the sensor data include data sampling, filtering segmentation, feature extraction, and classification for better decision support by upper layers.
- **Perception Layer** - This layer offers physical infrastructure of sensors and transposers orchestrated in a way that effectively provides sensory stimulus information. Sensors, multi-sensory interfaces and HPT devices are some of the hardware components referred in this layer as evident from Fig. 3.

Data gathered and processed by the Gateway is then transmitted through a wireless sensor network to decision support system over the cloud. HBC Activities and processes performed by architectural components are defined in a flow through Fig. 4. Our proposed system is remotely monitoring chemical senses of an ADHD patient, transmitting the information to a remote server. Finally, appropriate notifications are sent to predesignated related person and an intelligent decision support system. This whole process is divided into following four sequential phases:

Phase 1. Sensing and Transduction - Combination of wearable tactile T_x, olfactory O_x and gustatory G_x transducers gather sensory information from patient body. For simplicity, we employ any one Tactile Sensor ST_x as shown in Fig. 4 to monitor activity levels of the subject. Devices that monitor the chemical sensory perceptions of the patient are also mounted near patient. DG_x denotes a device for gustatory testing and similarly DO_x denotes a device for olfactory testing. Patient or an aide might operate these devices to provide manual sensory input. In this WBAN, least number of nodes are used to ensure user comfort and thus optimal reading of sensory information.

Each sensor node in the HBC based WBAN performs a series of computing tasks on the collected physiological signals in order to extract information about the patient. In case of tactile sensors, frequency of signals keeps varying, therefore we employ adaptive sampling to reduce sample data volume and to limit the sampling error. We prefer to have separate slots for storing the data of each chemical and wave form. Inputs to testing devices is stored in separate files. Data files are transmitted over the network using a middle ware. Communication protocols depend on the radio chip of the hardware platform; and a popular standard is IEEE 802.15.4.

Currently, our proposed work monitors taste and smell perceptions of the patient only once a day with the help of olfactory and gustatory test devices. This novel work is among the very first approaches towards automation of smell testing that is traditionally done via Sniffin' Sticks Test, the manual testing of olfactory performance. Chemical gustometry, through a solution application to the tongue, is traditionally used for testing patient's gustatory performance. As described in Section II, devices will gather data from the patient and HPT devices at physician's end and will reconstruct patient performance in perceivable formats as shown in Fig. 2.

Phase 2: HBS - The HBS node will receive sampled sensor data to analyze it for integrity, security, authenticity and reliability before transmitting the data to Phase 3.

Phase 3. HPT - Specialized HPT devices will reconstruct material properties of chemical senses via direct or indirect realization as evident from Fig. 2.

Phase 4. Classification and Clustering - Data from HPT devices is synchronized and time-stamped in order to prepare it for classification and clustering. Segmentation algorithms divide incoming data streams into discrete time intervals. Each segment has a multidimensional (feature) vector that is extracted from it. This feature vector is used for classification purposes. Sensor data and user inputs given to Test Machines are compared with pre-decided values determined by physicians. For example, activity levels traced by one of the Tactile Sensors mentioned as ST_x in Table I. Olfactory and gustatory profiles of the patient are generated by one of the Olfactory and Gustatory Devices, DO_x and GO_x, respectively. Values from these sensors and devices are compared with a predefined scale of symptoms. Using these thresholds, a classifier calculates patient's ADHD status.

ADHD criteria defined by the Diagnostic and Statistical Manual of Mental Disorders (DSM-V) is converted into measurable parameters which are in turn used as reference for classification of subjects. In this way, the system is able to classify subjects into four categories: Attention Deficit AD, Hyperactivity Disorder HD, combined Attention Deficit Hyperactivity Disorder ADHD, and simply non-ADHD. This information about the four categories of subjects are clustered on the basis of relative performance. Similar performance levels of attention or inattention, activity or hyperactivity are clustered into three levels: minimum, moderate, and maximum. Clustering helps in prognosis of subjects at risk of developing any or all categories of ADHD later in life. This step yields information about relative levels of performance of all subjects within the classified data.

V. Challenges

There are some implementation challenges in realization of HBC framework which we discuss here:

- Multiple sensors improve accuracy of data collection. It also reduces the risks of misdiagnosis but user comfort is compromised by sensor fusion. It is possible to use a single patch co-located sensors to monitor core ADHD symptoms like alertness, attention, movement, stress level and physical activity.
- Identification of symptoms that can be the cause of comorbidity thus Additional algorithms are required for this differentiation.
- Contact with a physical object is required to initiate sensations of smell, test and touch, and therefore, continuous monitoring of these three senses is difficult. While it is achieved for taste and touch with the help of tongue and tactile sensors, it is hard to access the olfactory receptors deep inside the nose.

VI. HBC Possible Applications

A. Packaging and Manufacturing

Several applications exist where HBC can be leveraged for service enhancement, e.g., as taste makers and quality check in food through odor and visual sensing, pharmaceutical, manufacturing domains, security and safety against fire and other such disasters in building automation domain, interactive marketing for products such as perfumes and gastronomical products. Such innovation can make way for a more holistic buying experience for consumers. Similarly, gas leakage sensors have been used in industrial setups to monitor leakages in order to avoid fatal accidents.

B. Umwelt Expansion

Umwelt expansion by enabling humans of perceiving a novel sense. A novel sense is one that has never been perceived for example, low frequency wave forms and inaudible frequency ranges. Holistic space exploration can be applied to planetary / exo-planetary research, search for water, organic compounds and other elements essential to sustain life, whereby a compound's taste, odor, texture and other physical properties are sensed and replicated at a remote location.

C. Miscellaneous Applications

Recreation of certain sensory experiences for education, wellness or entertainment can be made possible by HBC applications, by creating a wholesome experience for users. Meditation environments, real world-like experiences and virtual realities can be the next thing in personal care, gaming and entertainment industry.

VII. Conclusions

Human Bond Communication is a recent concept that can be practically useful in health-care, food and odour, and safety applications. The greatest need, however, is to implement the idea to promote monitoring continuously and remotely. Several attempts have been made in different directions and human umwelt expansion can be pursued to facilitate patients with sensory disabilities. In this work, we present several enabling technologies that can act as device equivalents of human tactile, gustatory and olfactory perceptions. We also propose a model architecture of HBC based application framework for monitoring and diagnosis of ADHD patient's body. Finally, we discuss challenges and trade offs that arise while trying to realize chemical senses for several human bond communication applications. Apart from health-care domain several other areas have been discussed where HBC can be leveraged for provision of ubiquitous services.

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